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Beam Breakup in a Solid-State Powered Linear Induction Accelerator

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***Abstract*— Scorpius is a new multi-pulse linear induction accelerator (LIA) for flash radiography of large-scale, explosively-driven hydrodynamic experiments. It has been proposed to use solid-state pulsed-power modules to provide the accelerating voltages for Scorpius. It is expected that this approach can provide four programmable 50-kV accelerating pulses to a single gap. Cascading these to form an LIA to accelerate four injected 2-kA, 2-MeV electron-beam pulses to 20-MeV is proposed. Since this high-current accelerator will have more than five times the number of cells as present radiography LIAs, it is natural to be concerned about the beam-breakup (BBU) instability. This concern is addressed using one of our beam dynamics codes. The results of these early simulations are presented here. They indicate that BBU can be suppressed to the same level as in designs powered by conventional pulsed power, if the calculated cell impedance can be achieved in practice. The magnetic focusing field required for this is of the same order as the field required for a conventionally powered LIA if the transverse impedance can indeed be constrained to the values obtained in simulations of the cell.**

I. Introduction

SCORPIUS is a new linear-induction accelerator (LIA) being developed for flash radiography of large hydrodynamic experiments driven by high-explosives [1]. The Scorpius beam injector will produce four 2-kA, 2-MeV pulses, which will be accelerated by the LIA to 20-MeV. These electron pulses will then be focused onto a bremsstrahlung radiation converter for point-projection imaging of the experiment [2]. The radiation pulse-lengths will be less than 60-ns FWHM, which is sufficient to provide stop-action radiographs of the experiment at four discrete times.

It has been proposed to power this accelerator with solid-state pulsed-power modules, which would provide considerable flexibility for programming of pulselengths and inter-pulse intervals to match the experiment being radiographed. The proposed solid-state pulsed power would provide 50-kV to the accelerating gaps. This gap voltage accounts for beam loading, so it is the full accelerating potential, 360 gaps would be needed to provide the required 18-MeV energy gain. This is more than five times the number of gaps in present radiography LIAs [3, 4], so the beam-breakup (BBU) instability is a concern. This article is an attempt to provide early insight into the extent of this problem for the proposed solid-state powered accelerator (SSA).

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II. Theory

Theory [5, 6, 7] predicts that, after a large number of cells (N), the maximum amplitude of the BBU asymptotes to $\max \xi(z) = \xi_0 \left[\gamma_0 / \gamma(z)\right]^{1/2} \exp\left(\Gamma_m\right)$, where subscript zero denotes initial conditions, and γ is the relativistic mass factor[1]. The exponent in this equation is the maximum growth factor

$$\Gamma_m\left(z\right) = \frac{I_b\, N\, Z_{tr}}{300} \left\langle \frac{1}{B} \right\rangle \quad , \tag{1}$$

where I_b is the beam current in kA, Z_{tr} is the transverse coupling impedance in Ohms/cm, B is the solenoidal guide field in kG, and $\langle \; \rangle$ indicates an average over the cells. This scaling of BBU growth has been experimentally validated [3, 8, 4, 9], and is unmistakable in computer simulations based on models of beam interaction with the cavities [10].

III. Simulations

Simulations of BBU growth have usually been performed using detailed axial dependence of the solenoidal focusing field (the so-called magnetic "tune") [10, 11]. Except for the periodicity of the magnetic field and inter-cellblock drifts, the tune details are largely unrelated to the LIA architecture. Therefore, it is useful to consider an approach that is independent of such details when assessing vulnerability various designs to BBU. As apparent in Eq.(1), instability suppression by the average of B^{-1} suggests using a uniform field in simulations. Because the theory underlying Eq.(1), has limits on B^{-1} that are exceeded in tunes with regions of low field strength, I have used the average of B itself in the denominator instead. As shown in Appendix A, the resultant growth in simulations using this ansatz is a close approximation to the growth using a fully detailed tune. Therefore, in this article we adopt the use of the average magnetic field between the first and last gap to obtain an analysis of growth unrelated to the tune details.

The SSA concept under consideration as an alternative to conventional pulse-forming transmission lines for Scorpius. Parameters for the proposed system relevant to BBU are listed

[1] The factor $\sqrt{\gamma_0 / \gamma}$ is a fundamental property of BBU wakefields sometimes called adiabatic damping [15].

in Table I [12]. The listed transverse impedance is derived from axisymmetric simulations with AMOS[2] [13] taking into account symmetry breaking by the voltage-drive rods (see Appendix B).

Table I. SSA Parameters

Parameter	Symbol	Units	Value
Beam Current	I_b	kA	2.0
Injected Energy	KE_0	MeV	2.0
Final Energy	KE_f	MeV	20.0
Gap Voltage	V_{gap}	kV	50.0
Number of Gaps	N		360
Gap Spacing	L_{cell}	cm	15.6
Transverse Impedance	Z_{tr}	Ω/cm	1.75
Magnetic Field	B	kG	< 1.5

We simulated BBU growth using our LAMDA beam dynamics code[3]. Our present version of LAMDA is limited to a maximum of 200 gaps, so I used the scaling of Eq. (1) to get a quick estimate before we could have the code revised, recompiled, and fully tested. That is, according to Eq.(1), halving the number of gaps, and doubling the transverse impedance would give the same growth rate. The 180 gaps of this model is well within the present capabilities of LAMDA. Furthermore, I also doubled the cell length and accelerating potential in order to maintain the full-scale accelerating gradient and adiabatic damping in the model. Thus, the LAMDA simulations were done with the scaled model parameters listed in Table II.

Table II. LAMDA Scaled Model Parameters

Parameter	Symbol	Units	Value
Beam Current	I_b	kA	2.0
Injected Energy	KE_0	MeV	2.0
Final Energy	KE_f	MeV	20.0
Gap Voltage	V_{gap}	kV	100.0
Number of Gaps	N		180
Gap Spacing	L_{cell}	cm	31.2
Transverse Impedance	Z_{tr}	Ω/cm	3.5
Magnetic Field	B	kG	< 1.5

Results of these "quick-look" simulations are plotted in Fig. 1 for two different strengths of magnetic guide field. For reference, the BBU growth in a simulation of DARHT-I using the full details of the nominal tune is also plotted. These results indicate that magnetic fields well within the range planned for the SSA will suffice to suppress the BBU to DARHT-I levels. The strength of the required magnetic field (~1 kG) is approximately the same as that required to suppress BBU in a conventionally powered Scorpius design (see examples in Appendix A).

Finally, in all of the simulations presented here, the initial excitation of the instability was with a sine wave at the resonant frequency. The corresponding experimental situation would be excitation with a powered kicker tuned to the resonant frequency, as was done on DARHT [14].

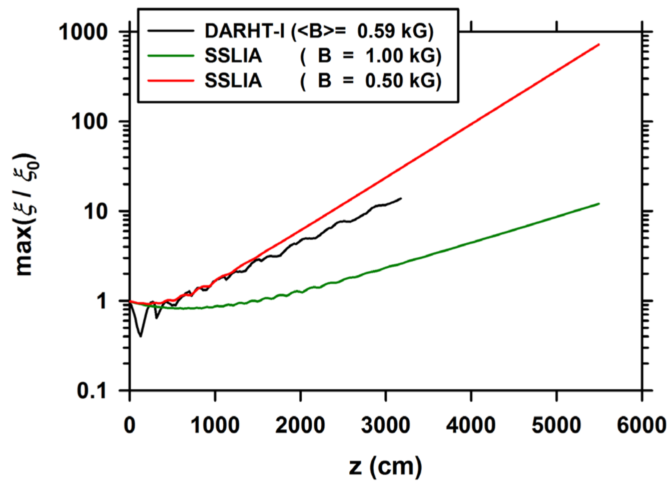

Fig. 1: Simulated BBU growth in the scaled model SSA. Red Curve; Uniform guide field B = 0.5 kG. Green Curve; Uniform guide field B = 1.0 kG. Black Curve; DARHT-I with nominal magnetic tune.

IV. Conclusion

A scaled model of the SSA architecture was evaluated for BBU growth using the LAMDA beam dynamics code. Results with a tune-neutral, uniform magnetic-focusing field showed that suppression to DARHT-I levels can be achieved with a solenoidal magnetic guide-field strength well within Scorpius requirements. The strength of the required magnetic field is approximately the same as that required to suppress BBU in a conventionally powered Scorpius design. Of course, this conclusion is contingent on being able to produce an induction cell with 1.75 Ω/cm transverse impedance or less. For future work, we plan to revise the LAMDA code to accept the full complement of gaps planned for the SSA.

Appendix A

BBU growth in an LIA depends on the details of the magnetic tune. For scoping studies and comparisons of LIA architectures and cell designs it is useful to use a methodology that is independent of these details, since there are many different strategies for tune design [11]. Using the average of the magnetic field in simulations is one approach to tune-neutral assessments. Here, three examples show that using the average field gives simulation results that are a close approximation to simulations with the detailed tune.

[2] AMOS is an acronym for Azimuthal Mode Simulator.

[3] LAMDA is an acronym for Linear Accelerator Model for DARHT, and DARHT stands for Dual Axis Radiography for Hydrodynamic Testing.

The first example is of the DARHT-I nominal tune.

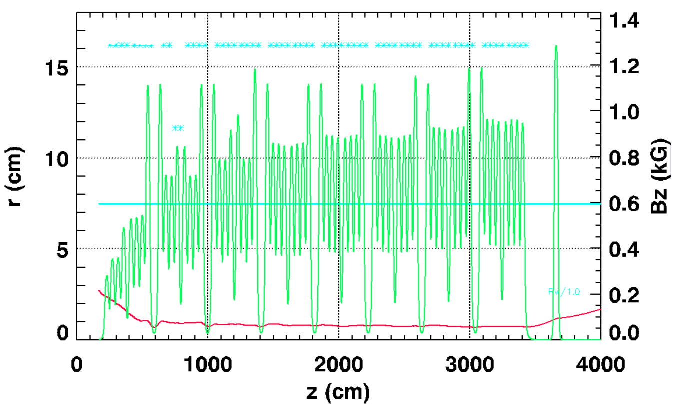

Fig. 2: Beam transport through the nominal tune of DARHT-I as simulated by the XTR envelope code. Green Curve; Solenoidal magnetic field on axis (Right Scale). Red Curve; Beam envelope radius (Left Scale). Cyan Line; Beam pipe radius (Left Scale). Cyan Asterisks; 250-kV gap voltages (with two exceptions).

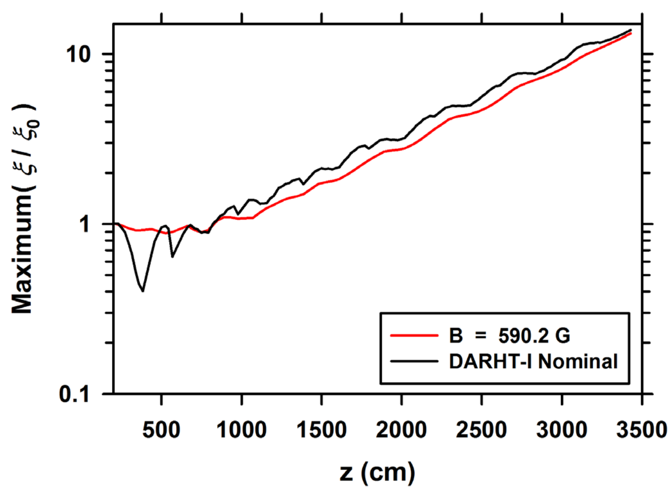

Fig. 3: LAMDA simulations of BBU growth in DARHT-I. Black Curve; Using full details of tune shown in Fig. 2. Red Curve; Using a uniform field equal to the average of the field shown in Fig. 2.

The next example is the tune designed for the Scorpius Conceptual design Report.

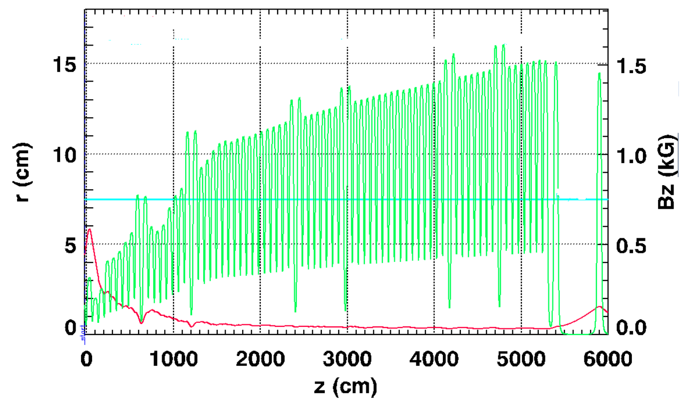

Fig. 4: Beam transport through the CDR tune for Scorpius as simulated by the XTR envelope code [11]. Green Curve; Solenoidal magnetic field on axis (Right Scale). Red Curve; Beam envelope radius (Left Scale). Cyan Line; Beam pipe radius (Left Scale).

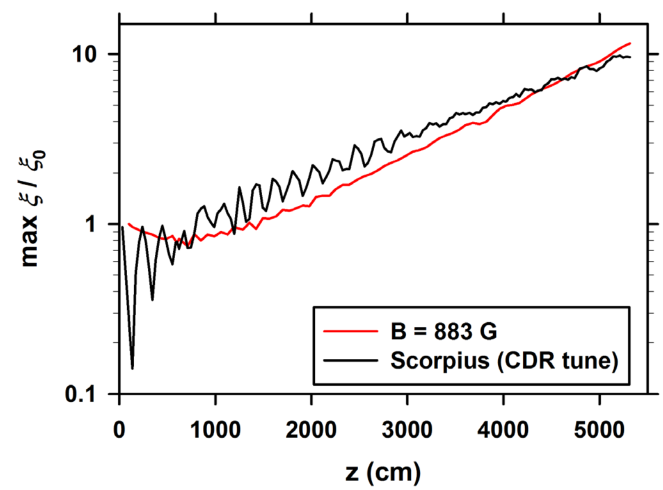

Fig. 5: LAMDA simulations of BBU growth in Scorpius. Black Curve; Using full details of CDR tune shown in Fig. 4. Red Curve; Using a uniform field equal to the average of the CDR tune shown in Fig. 4.

The final example is for the tune used for end-to-end transport and stability studies [ref, Yuan Wu] for the Scorpius Conceptual Design Report..

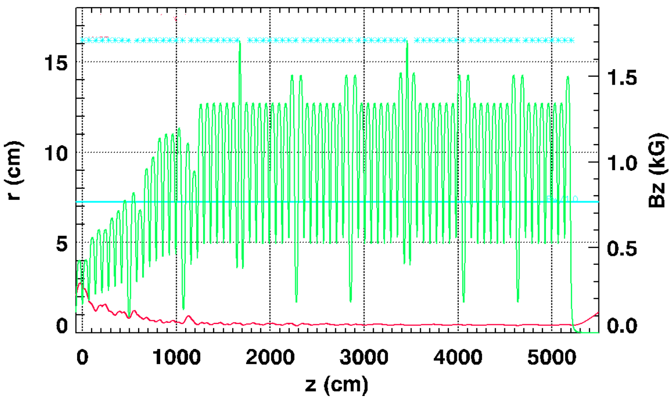

Fig. 6: Beam transport through the end-to-end tune of Scorpius as simulated by the XTR envelope code. Green Curve; Solenoidal magnetic field on axis (Right Scale). Red Curve; Beam envelope radius (Left Scale). Cyan Line; Beam pipe radius (Left Scale). Cyan Asterisks; 250-kV gap voltages.

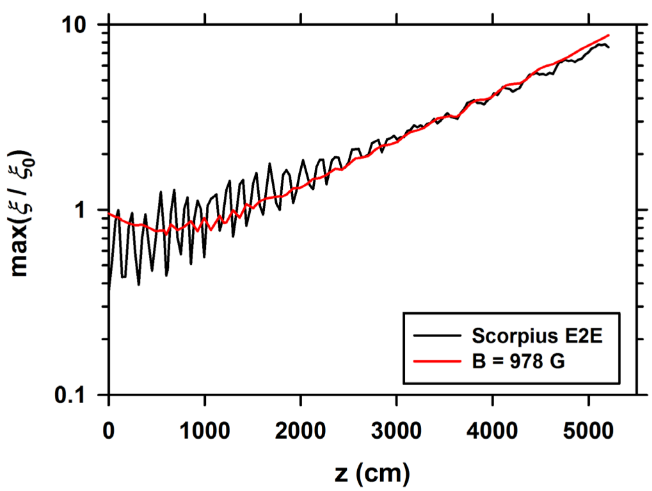

Fig. 7: LAMDA simulations of BBU growth in Scorpius with end-to-end tune (E2E). Black Curve; Using full details of E2E tune shown in Fig. 6. Red Curve; Using a uniform field equal to the average of the E2E tune shown in Fig. 6.

It is evident from these simulations that the using the uniform average field in LAMDA simulations yields results closely approximating simulations that include the full details of the magnetic tune.

Appendix B

The transverse impedance used for these simulations is based on the result of AMOS simulations (see Fig. 8). These results for an axisymmetric cavity give a peak impedance of ~250 Ω/m at ~400 MHz. Experimental measurements of DARHT-I cells showed that the impedance of an axisymmetric cavity was significantly reduced (28% - 30% reduction) when the symmetry-breaking drive rods and compensation resistors were installed (23% - 38% reduction). Therefore, I used 70% of the AMOS predicted impedance (175 Ω/m) as a conservative estimate for the Table I listing of SSA parameters. Furthermore, this impedance was doubled to 350 Ω/m for the 180-cell scaled model LAMDA simulations, as shown in Table II.

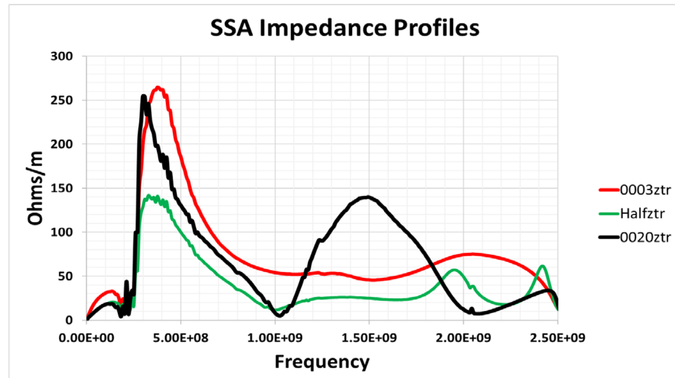

Fig. 8: AMOS simulations of SSA cell transverse impedance [12].

Acknowledgment

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